Experimental Study of Multipactor Suppression in a Dielectric-Loaded Accelerating Structure

J. G. Power,[1*] W. Gai,[1] S. H. Gold,[2] A. K. Kinkead,[3] R. Konecny,[1] C. Jing,[1] and W. Liu,[1]

[1]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
2Plasma Physics Division, Naval Research Laboratory, Washington, D.C. 20375, USA
[3]*LET Corporation, Washington, D.C. 20007, USA*

Abstract. High power tests are currently being conducted on RF-driven dielectric-loaded accelerating (DLA) structures to determine their viability as traveling-wave accelerators. These tests are a collaborative effort between Argonne National Laboratory (ANL) and the Naval Research Laboratory (NRL). In a previous high power test, single-surface multipactor was reported to be capable of absorbing more than half of the RF power incident on an alumina-based DLA structure. In this paper, we report on the most recent set of high power tests that are attempting to further understand multipactor and eventually suppress it. Several methods were employed to suppress multipactor including: the use of a magnetic field; a TiN surface coating; and a different dielectric material (Magnesium-Calcium-Titanate based). The effectiveness of these three methods are presented and discussed in the paper.

INTRODUCTION

Dielectric-based accelerating structures are currently being actively pursued as high-gradient alternatives to conventional iris-loaded copper structures. In particular, the cylindrical, RF-driven, dielectric-loaded accelerator (DLA), in which a uniform dielectric-lined metal tube replaces the metal disk-loaded structure [1, 2] offers a simpler geometry with acceleration efficiency comparable to metallic structures and the potential to operate at higher acceleration gradients. The proposed use of dielectric-based structures for acceleration dates back to the 1950s [3], but experimental testing to examine if these devices are capable of high-power operation has only recently begun [4, 5]. For the last several years, a program has been under way at Argonne National Laboratory, in collaboration with the Naval Research Laboratory (NRL), to develop cylindrical, RF-driven, dielectric-loaded accelerating (DLA) structures, with the ultimate goal of demonstrating a compact, high-gradient linear accelerator based on this technology [6].

Structure development takes place at ANL and includes all the low-power tasks ranging from design and fabrication to network analyzer bench-top measurements and vacuum testing. In the first stage of the program, several structures designs were tested (at low-power) at ANL before the first high power test was carried out. During these tests [1] several issues were addressed including (1) development of an efficient

[*] *jp@anl.gov

CP737, *Advanced Accelerator Concepts: Eleventh Workshop,*
edited by Vitaly Yakimenko

DIELECTRIC LOADED ACCELERATING STRUCTURE

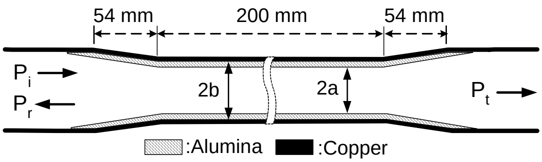


FIGURE 1. Cross section of the cylindrical, alumina DLA structure. (a=5 mm, b=7.185 mm)

RF coupling scheme; (2) demonstration that gas absorption didn't prevent good operating vacuum; and (3) demonstration that the RF properties of the structure were not overly sensitive to temperature fluctuations.

Once a structure has been successfully developed at ANL, it is transported to NRL's 11.424 GHz Magnicon Facility for high power testing. The purpose of the high power test is ultimately to demonstrate high-gradient operation of the DLA structure and to discover and correct any phenomena that prevent such operation. The first series of high power tests carried out at NRL [7] were conducted on an $Mg_xCa_{1-x}TiO_3$-based (MCT-based) DLA structure and revealed arcing in the input coupler at an incident power (P_{inc}) level of approximately 0.5 MW, similar to what was observed by Fang et al. [5]. Due to the failure of the input coupler, the DLA structure was subsequently redesigned [8] and, a second series of high power tests were carried out on the new DLA structure. This structure was successfully high power tested [9] to P_{inc} = 5 MW without any signs of RF breakdown. However, a new problem was observed at this higher power level, anomalous absorption of the incident power which was later attributed to multipactor.

Multipactor is an electron multiplication process that can take place on surfaces exposed to RF fields in vacuum. Multiplication occurs when an electron gains energy from the RF field, and strikes the surface with an impact energy between the first cross-over energy (e_1 , typically in the range of 10-100 eV) and the second cross-over energy (e_2 , typically in the range of 1-10 keV). Multipactor can lead to a variety of deleterious effects, but the one that is of greatest concern for the DLA structure is its ability to absorb large amount of power from the RF field. Further details about multipactor are not given here, since many references exist on the topic [10-12] including a paper recently published by our collaboration [13] that describes the first experimental observation of multipactor in a DLA structure along with a model that explains the multipactor-induced power absorption. In the remainder of this paper, we will discuss the third series of high power tests which were recently conducted and were intended to deepen out understanding of multipactor in DLA structures and the methods to suppress it.

Multipactor effects were studied for two basic types of DLA structures, an alumina-based and an MCT20-based. Both structures consist of a uniform dielectric-lined copper tube in the central region and dielectric-lined tapered transitions at both ends used for matching to the all-copper tube. They are also both constant-impedance, 11.424 GHz, traveling-wave (TW) accelerators operating in the TM_{01} mode. The

TABLE 1. Parameters for the Alumina and MCT based 11.424 GHz DLA structures.

Parameter	Alumina	MCT
Dielectric Material	Al_2O_3	$Mg_xCa_{1-x}TiO_3$
Dielectric Constant	9.5	20
Inner Radius	5 mm	3mm
Outer Radius	7.185 mm	4.56mm
Power needed to support gradient of 1 MV/m	80 kW	27 kW
Group Velocity	0.134 c	0.057c

alumina DLA structure is shown in Figure 1 and its parameters are shown in Table 1, while the MCT structure is described in detail in Reference [14] and its parameters are also summarized in Table 1.

In addition to the high power tests carried out on these two structures, a second alumina-based structure was prepared that was identical to the alumina-structure just described except that the inner alumina surfaces were coated with a 20-nm thick layer of TiN. This structure is called the coated-alumina structure in order to differentiate it from the non-coated structure described above. All told then there were three separate structures whose multipactor effects were studied: the non-coated alumina structure; the coated alumina structure; and the non-coated MCT structure.

EXPERIMENTAL SETUP

All high-power tests were conducted at the 11.424-GHz Magnicon Facility at the Naval Research Laboratory [15]. A detailed description of the experimental procedures used during the high power test is given elsewhere in these proceedings [6, 15] and will not be repeated here. Briefly, power from the magnicon is first coupled from rectangular to cylindrical copper waveguide with a $TE_{10} - TM_{01}$ mode converter [8] and then into the DLA structure (Fig. 1). Following bakeout and RF conditioning, the incident (P_{inc}), reflected (P_{ref}), and transmitted (P_{tr}) RF powers were measured with directional couplers as P_{inc} was raised from low to high values. Lastly, a solenoid surrounded the coated alumina DLA structure, during the high power tests, so as to produce an axial magnetic field in the region of the dielectric surface. This produced a magnetic field that was approximately parallel to the surface of the dielectric in the central region of the tube and could be varied in strength from 0 to about 300 Gauss.

RESULTS AND DISCUSSION

Multipactor has been experimentally studied for four different configurations. These are: (1) a non-coated alumina DLA structure; (2) coated alumina DLA structure with no magnetic field; (3) coated alumina DLA structure with a magnetic field; and (4) a non-coated MCT DLA structure. In this section we compare and contrast these four configurations.

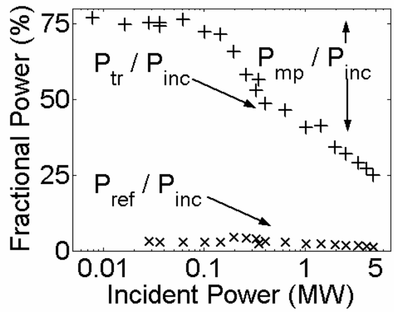


FIGURE 2. The measured values of the three fractional powers (in percentage) as a function of incident power during the high-power test of the DLA Structure. The decrease in the fraction of transmitted power is caused by the increase in the fraction of power absorbed by multipactor.

The Standard: The Non-coated Alumina DLA structure

In this section, we briefly summarize the original experiment where multipactor in a non-coated, alumina DLA structure was discovered. This serves two purposes: it explains the dominant multipactor effect observed (multipactor-induced power absorption) and defines a standard by which the other three cases studied can be compared.

After a short conditioning period of the non-coated, alumina DLA structure, the incident power was raised from low power to 5 MW ($E_z \approx$ 8 MV/m) at an RF pulse length of 150 ns FWHM, with no sign of RF breakdown during the conditioning process. As can be seen in Figure 2, the fraction of power transmitted through the tube, P_{tr}/P_{inc}, was approximately 75% (which is consistent with network analyzer measurements) below ~0.1 MW, but decreased rapidly above that point. Since there was not a corresponding rise in the fraction of reflected power, P_{ref}/P_{inc}, the roll off above the knee in the data (near 0.1 MW) was eventually understood to mean that some fraction of the incident power was being absorbed by multipactor or, $P_{mp}/P_{inc} \neq 0$. As explained in the reference, this knee occurs at the location of the first cross-over energy, e_1. At the highest incident power level, multipactor absorbed approximately 50% of the incident power or, $P_{mp}/P_{inc} \approx 50\%$.

TiN Coating

In this section we compare the results from the high power tests of the alumina DLA structure without a coating, "the non-coated structure" and the alumina DLA structure with a 20-nm thick TiN coating, "the coated structure." The only experimentally measured parameter that is discussed in this section is the fraction of transmitted power, P_{tr}/P_{inc}. We do this since it is the clearest indicator of multipactor. Note that in Figure 3 we plot the normalized fraction of power that is transmitted through the waveguide. The reason we normalize the transmitted power is

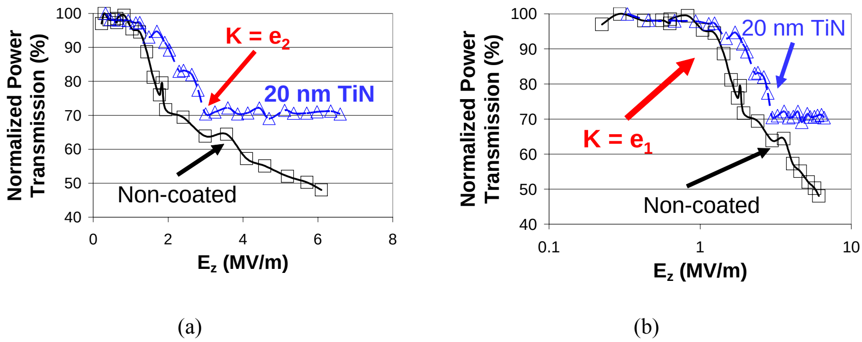


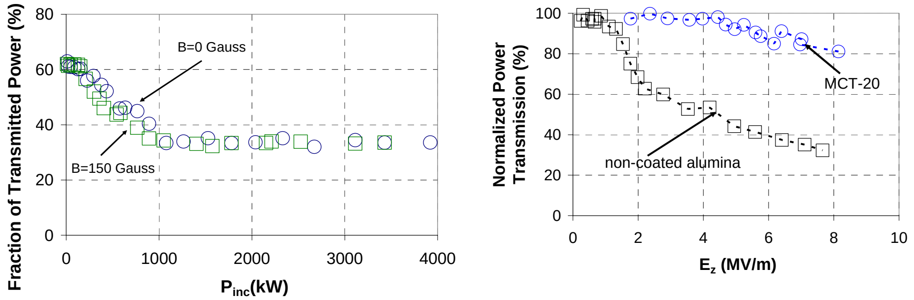
FIGURE 3. The normalized fraction of transmitted power P_{tr}/P_{inc} vs. acceleration gradient E_z for both the coated (triangles) and non-coated (squares) structures. A larger fraction of the transmitted power is absorbed in the non-coated DLA structure than the TiN-coated DLA structure.

because the value of P_{tr}/P_{inc} at low power varies for the different structures due to mechanical and assembly variations. Normalizing P_{tr}/P_{inc} to 1 at low power allows for easy comparison between different tubes.

In Figure 3, we plot the normalized fraction of transmitted power vs. the acceleration gradient. As one can easily see, a larger fraction of the transmitted power is absorbed in the non-coated structure than the coated structure at power levels above multipactor threshold. In other words, the fraction of power absorbed by multipactor, P_{mp}/P_{inc}, is less for the case of the coated structure than the non-coated structure. However, while the amount of absorbed power is less for the coated structure, it is still a substantial fraction of the incident power, approximately 30% at high power. As stated above, the multipactor threshold (the first knee in the data near 1 MV/m) occurs because the impact energy of the electrons is equal to $e_1 \approx 60\, eV$ (Fig. 3b) for alumina. The second knee in the data, near 3 MV/m, corresponds to an impact energy of 1.5 keV (Fig. 3a) and is believed to correspond to the second cross-over energy of the coated structure or $e_2 \approx 1.5\, keV$.

Magnetic Field

In this section we discuss the affect of an axial magnetic field on the multipactor-induced power absorption. Measurements of the transmitted power were made of magnetic field strengths of approximately 0, 75, 150, 225, and 300 Gauss. Since the effect of the solenoid was not very strong we only show the transmission for the case of 150 Gauss for clarity (Fig. 4a). As can be seen, a solenoidal magnetic field did not have a dramatic effect and may have even caused a slight increase in power absorbed by multipactor in the central region where the incident power is between 100 and 1000 kW.



a b

FIGURE 4. Transmitted power as a function of incident power (a) with and without a magnetic field. (Circles = solenoid off; Squares=solenoid on and B=150 Gauss.); (b) for different materials

$Mg_xCa_{1-x}TiO_3$

In this section we compare the level of power transmitted power absorption in the MCT-20 dielectric structure with that of the standard non-coated alumina structure. Since multipactor is a secondary electron emission (SEE) avalanche process, and alumina is known to have a relatively high value for the SEE coefficient, it is reasonable to suppose that other materials, with lower SEE coefficients, may lose less power to multipactor. Although the value of this coefficient for MCT is unknown to us, we decided to study this since it is a readily available high-quality commercial microwave ceramic.

In Figure 4b, we once again plot the normalized fraction of transmitted power vs. the acceleration gradient. The power absorbed by multipactor for the MCT-based and alumina-based DLA structures are shown on the same plot in Figure 4b. From this, one can see that there is significantly less multipactor-induced power loss in the MCT structure than the alumina, thus implying that the materials have very different SEE coefficients. This shows that it may be possible to abate the multipactor effects by a judicious choice of materials.

CONCLUSIONS

Multipactor in DLA structures was studied for 4 different cases. Compared to the standard, a non-coated alumina DLA structure, the following results were obtained. (1) The 20-nm thick TiN coating showed a steep reduction in the multipactor-induced power absorption compared to the standard. (2) The solenoidal magnetic field had only a minor effect on the absorption. (3) The MCT-based DLA structures showed substantially less power absorption than the standard. In other words, while the solenoidal magnetic field did not have a large effect, the TiN coating and the different material (MCT) appear to be promising candidates for suppressing multipactor. In the future we plan to continue pursuing methods to further suppress the multipactor.

ACKNOWLEDGMENTS

This work was supported by the Office of High Energy Physics, US Department of Energy and by the US Office of Naval Research.

REFERENCES

1. P. Zou et al., Rev. Sci. Instrum. 71 2301 (2000).
2. E. Chojnacki et al., J. Appl. Phys. 69 9 (1991).
3. G. Flesher et al., AIEE Trans. 70 887 (1951).
4. S. H. Gold and W. Gai, "High-Power Testing of 11.424-GHz Dielectric-Loaded Accelerating Structures," in Proceedings of the 2001 Particle Accelerator Conference, edited by P. Lucas and S. Webber, Piscataway, New Jersey: Institute of Electrical and Electronic Engineers, 2001, pp. 3984–3986.
5. J.-M. Fang, T.C. Marshall, M.A. LaPointe, and J.L. Hirshfield, *"An Experimental Test of a Microwave Inverse Cerenkov Accelerator,"* in Proceedings of the 2001 Particle Accelerator Conference, edited by P. Lucas and S. Webber, Piscataway, New Jersey: Institute of Electrical and Electronic Engineers, 2001, pp. 4020-4022.
6. S.H. Gold et al., *"Development of a 20 MeV Dielectric-Loaded Accelerator Test Facility,"* paper in these proceedings.
7. J.G. Power et al., *"High Power Testing of ANL X-band Dielectric Loaded Accelerating Structures,"* in Advanced Accelerator Concepts, edited by C. E. Clayton and P. Muggli, AIP Conference Proceedings 647, New York: American Institute of Physics, 2002, pp. 556–564.
8. W. Liu, C. Jing, W. Gai, R. Konecny, and J. G. Power, "New RF Design for 11.4 GHz Dielectric-Loaded Accelerator," in Proceedings of the 2003 Particle Accelerator Conference, edited by J. Chew, P. Lucas, and S. Webber, Piscataway, NJ: Institute of Electrical and Electronics Engineers, 2003, pp. 1810–1812.
9. J.G. Power et al., "*High Power Testing of X-band Dielectric-Loaded Accelerating Structures*," in Proceedings of the 2003 Particle Accelerator Conference, edited by J. Chew, P. Lucas, and S. Webber, Piscataway, NJ: Institute of Electrical and Electronics Engineers, 2003, pp. 1810–1812.
10. R.A. Kishek, Phys. Rev. Lett. **75** 1218 (1995).
11. L.-K. Ang et al., IEEE Trans. Plasma Sci. **26** 290 (1998).
12. R.A. Kishek et al., Phys. Rev. Lett. **80** 193 (1998).
13. J. G. Power, W. Gai, S. H. Gold, A. K. Kinkead, R. Konecny, C. Jing, W. Liu, and Z. Yusof, Phys. Rev. Lett. **92**, 164801 (23 April 2004).
14. C. Jing et al., *"High Power RF Test on X-band $Mg_xCa_{1-x}TiO_3$ Based Dielectric-Loaded Accelerating Structure,"* paper in these proceedings.
15. S. H. Gold, A. K. Kinkead, O. A. Nezhevenko, V. P. Yakovlev, J. L. Hirshfield, A. L. Vikharev, O. A. Ivanov, S. V. Kuzikov, A. M. Gorbachov, W. Gai, R. Konecny, and J. G. Power, "High Power Accelerator R&D at the NRL 11.424-GHz Magnicon Facility," in *Advanced Accelerator Concepts—Tenth Workshop*, Mandalay Beach, CA, 22–28 June 2002, AIP Conference Proceedings 647, edited by C.E. Clayton and P. Muggli (American Institute of Physics Press, Melville, NY, 2002), pp. 439–447.